# Matched wideband low-noise amplifiers for radio astronomy

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Two packaged low noise amplifiers for the 0.3–4 GHz frequency range are described. The amplifiers can be operated at temperatures of 300–4 K and achieve noise temperatures in the 5 K range ($<0.1$ dB noise figure) at 15 K physical temperature. One amplifier utilizes commercially available, plastic-packaged SiGe transistors for first and second stages; the second amplifier is identical except it utilizes an experimental chip transistor as the first stage. Both amplifiers use resistive feedback to provide input reflection coefficient $S11 < -10$ dB over a decade bandwidth with gain over 30 dB. The amplifiers can be used as rf amplifiers in very low noise radio astronomy systems or as i.f. amplifiers following superconducting mixers operating in the millimeter and submillimeter frequency range. © *2009 American Institute of Physics.* [DOI: 10.1063/1.3103939]

## I. INTRODUCTION

Very low noise, wide bandwidth, cryogenic microwave amplifiers are much in demand for radio astronomy and low temperature physics research. They are needed as rf amplifiers in large numbers for focal-plane arrays or arrays of telescopes such as the Square Km Array.[1] In addition they are required as i.f. amplifiers for millimeter and submillimeter wave receivers utilizing superconducting mixers.

For the last 20 years amplifiers utilizing high-electron-mobility field-effect transistors, usually on indium-phosphide substrates, have been used with excellent results in these applications.[2] However, in the last few years very high performance silicon bipolar transistors with germanium alloyed in the base region (SiGe)[3] have become available with rapid development spurred by the wireless communication market. The advantages of the SiGe amplifiers to be described in this paper are (1) good input impedance match over a decade of bandwidth extending to low frequencies, (2) better gain stability due to the vertical bipolar transistors in deference to near-surface, field-effect transistors, which exhibits transconductance fluctuations with a 1/F spectrum, (3) slightly lower noise (2.6 K versus 4 K) at 17 K as measured in the same test set, (4) availability of complementary metal-oxide semiconductor (CMOS) digital functions in the same integrated circuit (IC) process, and (5) riding a much more widely funded transistor development effort that should lead to higher frequency and higher performance in the near future.

In a previous paper[4] we have developed a theoretical noise model based on dc *I*-*V* measurements of the transistor and a simplified small-signal equivalent circuit. This was followed by measurements of the complete small signal model and relating the noise model to fundamental limits to the noise of a feedback amplifier.[5] These papers show that the dc current gain $\beta$ at the temperature of operation, as shown in Table I, is a key parameter for selection of a transistor for low noise at low microwave frequencies (well below the Ft, which is typically $>60$ GHz). On this basis an experimental STMicrolelectronics (ST) transistor,[6] type BipX1, was chosen for the first stage of the amplifier, which will be described as the "ST" amplifier in this paper. A second amplifier, termed as "NXP" amplifier, utilizes the NXP BFU725A transistor, which is commercially available in a plastic package. Both amplifiers utilize the BFU725A as the second stage.

It should be noted that other parameters of both the transistor and the circuit determine the amplifier noise. These are the base and emitter resistance, the transconductance relative to its theoretical value, the input circuit losses, the feedback resistor, and at higher frequencies the unity short-circuit current-gain frequency ($f_t$) of the transistor. These terms are considered in our previous paper but will not be further discussed in this paper, which concentrates on the construction and measured results for two amplifiers which are directly applicable to state-of-the-art radio astronomy systems.

The amplifiers utilize discrete transistors rather than ICs. A discrete transistor approach allows much flexibility in the design, rapid utilization of the latest transistors, requires less knowledge on the transistor model, and low cost for small quantities. However, an IC matched cryogenic amplifier with excellent performance has recently been developed and submitted for publication[7] and a resistive feedback on IC differential amplifiers including differential input has been reported.[8]

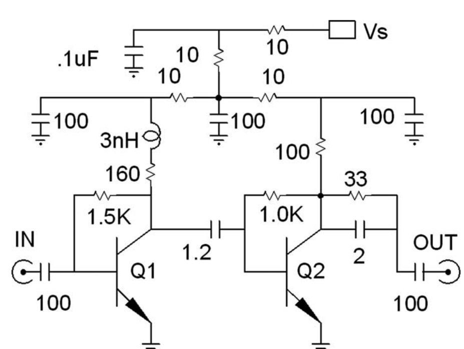


FIG. 1. Schematic of the amplifier. Capacitor values are in picofarad. Microstrip line lengths are not shown but are relevant above 2 GHz and have been included in the CAD analysis.

 

TABLE I. Current gain for various SiGe transistors at 300 and 17 K and current density of 1 mA/$\mu$m$^2$.

| Device type | Beta at 300 K | Beta at 17 K |
|---|---|---|
| ST BipX1 (VBF03) | 2200 | 18 000 |
| ST BipX2 (RYV24) | 1000 | 20 000 |
| NXP BFU725A | 600 | 5000 |

## II. DESIGN APPROACH

The amplifier design was first determined by an approximate but simple low-frequency analytical approach outlined below. This was then followed by computer-aided design (CAD) analysis of $S$ parameters and noise versus frequency with a microwave circuit simulator[9] using an approximate model of the transistor. Accurate modeling of the transistor is in process and should result in further optimization and IC implementation of the circuit

A schematic of the amplifier is shown in Fig. 1. Considering first the dc bias conditions, note that for the high beta shown in Table I, there is $<20$ mV drop across the collector to base feedback resistor. Thus, $V_{CE}=V_{BE}\sim 0.8$ V, and the collector current is determined by the supply voltage minus $V_{CE}$ divided by the resistance between supply and collector. For the first stage this is $\sim 6$ mA, and for the second stage this is $\sim 9$ mA for $V_S=2$ V. Restricting $V_{CE}=V_{BE}$ has some effect on the collector to base capacitance but this is not a major effect at the frequencies we are considering.

The collector current determines the transconductance of each transistor as $I_C/V_T$, where $V_T=\sim 28$ mV at room temperature and $\sim 7$ mV at 15 K. The voltage gain of stage 1 is thus 34 with 160 $\Omega$ collector load and $I_C=6$ mA at 300 K or 1.5 mA at 50 K. The input resistance of stage 1 at low frequencies is dominated by the feedback resistance, 1.5 K divided by the voltage gain to give 44 $\Omega$—a good match to a 50 $\Omega$ generator. It can be shown that the noise contributed by the feedback resistor is approximately the ratio of 50 $\Omega$ to $R_{fb}$ times the physical temperature of the resistor. For $R_{fb}=1.5$ K this is 10 K at 300 K and 0.5 K at 15 K.

The CAD circuit analysis revealed that the frequency range could be extended by adding a 3 nH inductor in the collector load of Q1, by adding a line length to the feedback resistor, and by including the 1.2 and 2 pF capacitors shown in Fig. 1. Note that the 1.2 pF capacitor between stages provides a high pass filter to flatten the gain and the output 2 pF capacitor improves the output impedance match.

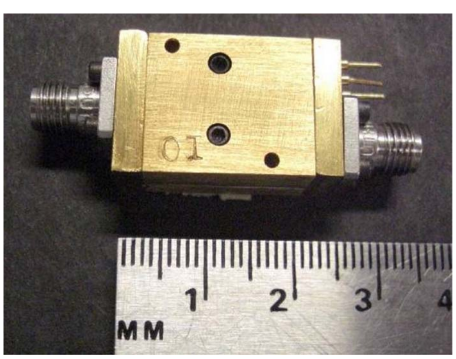


FIG. 2. (Color online) Photograph of the completed amplifier. Two center screws clamp a tight sandwich of top cover, PC board, and a flat bottom base. SMA connector screws extend into the top cover and base. Module material is gold-plated brass.

FIG. 3. (Color online) Inside view of cover over the PC board. Note that the cover provides a narrow channel above the active portion of the circuit to satisfy the low output-to-input coupling described in the text.

## III. MODULE DESCRIPTION

Both amplifiers utilize discrete transistors mounted on printed-circuit boards installed in a split-block coaxial fixture, as shown in Figs. 2–4. The two amplifiers are identical other than the input transistor and small changes in some of the surface mount parts which can be optimized for input and output matches, noise, and gain flatness. The wire bonding pattern for the ST chip transistor mounted in a via hole is shown in Fig. 5.

The packaging of the discrete transistors into a shielded module with coaxial connectors is extremely important. The major factors affecting the mechanical design are as follows:

(1) Output-to-input coupling. The transistors provide $>30$ dB of gain with output separated from the input by

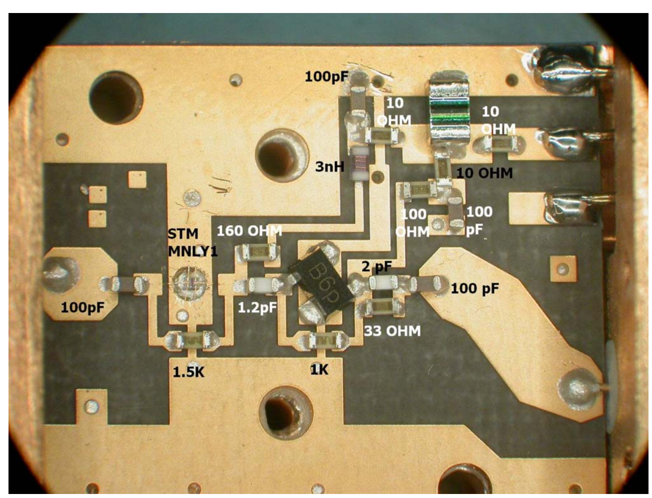


FIG. 4. (Color online) Interior view of the ST LNA module. The ST chip is in a plated-through hole with details shown in Fig. 5; the NXP transistor second stage is in the black rectangular epoxy package in the center of the photograph. The NXP module is similar but with a second NXP transistor soldered in the first stage location. All other components are standard surface mount parts soldered to a Rogers 5880 0.762 mm thick circuit board.

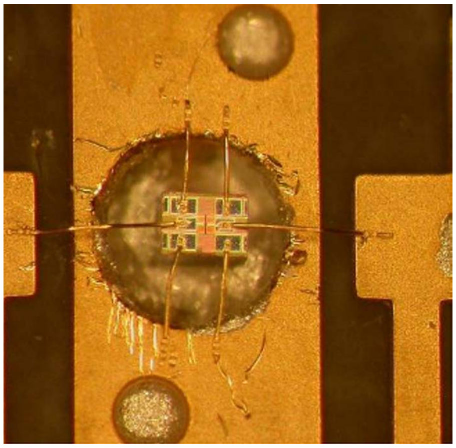

FIG. 5. (Color online) Closeup of STM discrete transistor chip mounted in a 1.2 mm diameter plated-through via. The four top and bottom bond wires are for grounding the emitter while the horizontal bond wires are for base input and collector output. The bond wires are 17 $\mu$m diameter gold.

<1 cm and extraneous coupling in the −40 dB range can cause large effects including oscillation. The reduction in this coupling requires a tight enclosure (see Fig. 3) over the microstrip printed circuit boards with a channel width, which is cut off for waveguide modes in the frequency range over which the amplifier has gain.

(2) Low-inductance grounds. The circuit needs grounds for transistor emitters and bypass capacitors. These should be considered in the CAD analysis and should typically have <0.2 nH inductance. Many plated-through vias are used on the printed circuit board for this purpose.

(3) Feedback resistor path length. The total length in the feedback resistor path causes a time delay and resulting phase shift in the feedback. This is modeled by cascaded transmission lines in the CAD analysis and an optimum length (not the shortest length) was found.

(4) Input circuit loss. This is important for low noise in any low noise amplifier. For this reason a very short input line, no impedance transformation or filtering, and a relatively thick (0.76 mm), low dielectric constant (2.2) were selected.

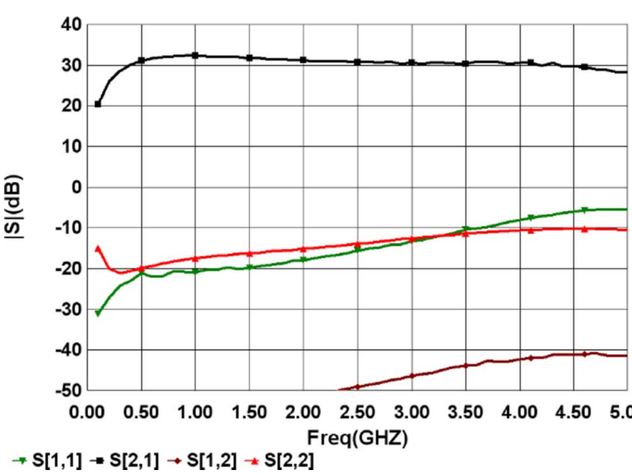


FIG. 6. (Color online) $S$ parameters of ST LNA at 300 K and 2 V, 15 mA bias.

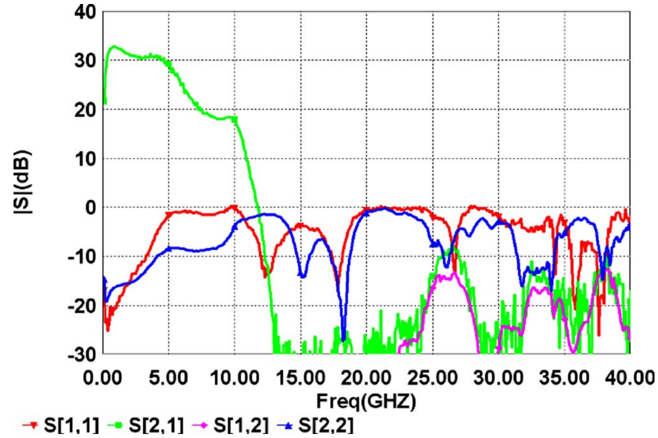


FIG. 7. (Color online) $S$ parameter of the ST LNA at 300 K with 2 V, 15 mA bias.

(5) Resonance between capacitors. It is usually necessary to implement a small bypass capacitor (say, 100 pF) near the transistor for microwave frequencies and a large capacitor (say, 0.1 $\mu$F) further away for lower frequency radio frequency interference (RFI) and static protection. The path length between the two capacitors provides an inductance, which can result in a high impedance and circuit instability. Small resistors are thus utilized between the capacitors to dampen this resonance.

## IV. RESULTS

### A. Scattering (*S*) parameters

The module $S$-parameters with 50 $\Omega$ reference were measured at 300 K for each amplifier from 0.1–40 GHz with an Anritsu vector analyzer. The ST amplifier $S$-parameters were also measured at 17 K with a little change when the bias was changed from the 300 K value of 2 V, 15 mA to 1.5 V, and 6 mA at 17 K. A typical result for the 0–5 GHz range is shown in Fig. 6.

The NXP amplifier had identical gain when biased to 2.3 V, 24 mA and had >10 dB input return loss from 0.1 to 4.5 GHz. To check for unwanted effects outside of the frequency range of the amplifier, the $S$-parameters were measured to 40 GHz, as shown in Fig. 7. Note that log magnitude of $S21$, $S11$, and $S22$ all remain under 0 dB at higher frequencies as desired for stability.

As a test of output-to-input coupling, the $S$-parameters were measured with no dc bias applied and a peak of −11 dB at 9.5 GHz was measured for $S12=S21$ (since the circuit is passive). This peak is mostly due to the signal path

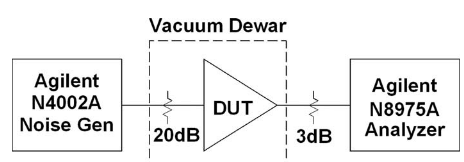


FIG. 8. Cryogenic noise test configuration. The cooled 20 dB attenuator at input of the device under test provides a calibrated low temperature input termination and greatly increases the accuracy of low noise measurements. This test set has been calibrated to ±1 K accuracy.

TABLE II. Noise and gain at 1.4 GHz of both LNAs as a function of temperature and bias.

| LNA | Temperature (K) | dc (V) | dc (mA) | (*P*) (mW) | *Tn* (K) | *G* (dB) | *S*11 (dB) |
|---|---|---|---|---|---|---|---|
| ST | 17 | 1.3 | 3.8 | 5 | 3.5 | 32.2 | NM |
| ST | 17 | 2 | 12.5 | 25 | 2.6 | 39.9 | NM |
| NXP | 17 | 1.7 | 10 | 17 | 6.4 | 32.8 | NM |
| NXP | 17 | 1.4 | 5.6 | 8 | 6.9 | 29.8 | |
| ST | 50 | 2 | 12.2 | 24 | 7.0 | 30.0 | NM |
| ST | 300 | 2 | 15.2 | 30 | 66 | 32.6 | −18 |
| ST | 300 | 3 | 27.6 | 83 | 55 | 36.5 | −12 |
| NXP | 300 | 2.3 | 23.6 | 54 | 90 | 30.5 | −11 |

through the feedback resistors and becomes −28 dB when power is applied and negative feedback is active.

### B. Noise

The noise temperatures of both amplifiers were measured at 300 and 17 K. The configuration for the 17 K measurements is shown in Fig. 8.

The noise temperature and gain of the NXP amplifier at 300 and 17 K (note the scale change) are shown in Fig. 9. At 17 K the noise of the amplifier is under 8 K from 0.5 to 4 GHz.

The noise and gain of the ST LNA at 17 K are shown in Fig. 10. At minimum noise bias the noise is under 3 K from 0.5 to 3 GHz, while at a low power (5 mW) bias the noise is under 5 K from 0.3 to 4 GHz. A summary of the noise, gain, and *S*11 of both amplifiers at 300 and 17 K is presented in Table II.

### C. Large signal performance

The large signal performance of the ST low noise amplifier (LNA) at a temperature of 300 K and 2 V, 15 mA bias was measured in two ways. The first was the conventional two-tone measurement with equal power signals applied at 1.6 and 2.0 GHz. The second order product at 3.6 GHz and third order product at 2.4 GHz were then measured as a function of input power. The second and third order intercepts were determined to be −10.6 and −16.4 dBm, respectively, and referred to input. The intercepts referred to output are ∼32 dB higher.

A second test of the large signal performance was the application of one large signal at 2.1 GHz and one small signal at 3.43 GHz. The 1.33 GHz mixing product was then measured as a function of the large signal power. This simulates the case of one large RFI signal acting as a local oscillator mixing with other low power RFI signals. The conversion loss of this mixing is independent of the small signal power (≪large signal power) but is a function of the large signal power, as shown in Fig. 11. The conversion loss peak of 19 dB was at the large signal output power of −3 dBm, which also corresponded to the 1 dB gain compression point. Thus, RFI signals referred to input of −35 dBm at 2.1 GHz and −60 dBm at 1.33 GHz would produce RFI of −79 dBm at 3.43 GHz, which is still 43 dB above the −122 dBm receiver noise in a 1 MHz bandwidth.

## V. CONCLUSIONS

We have described two complete amplifiers with a new transistor technology, SiGe HBT, which can be applied to

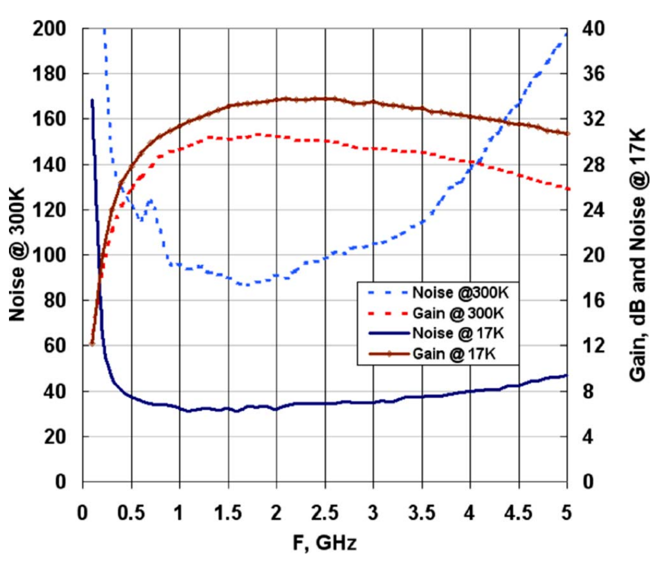


FIG. 9. (Color online) Gain (upper curves with scale at right) and noise of NXP LNA at 300 K (bias 2.3 V, 24 mA) and 17 K (1.7 V, 10 mA). Note that the noise at 17 K uses the right-hand scale and the noise at 300 K uses the left-hand scale (i.e., 90 K noise at 1.4 GHz).

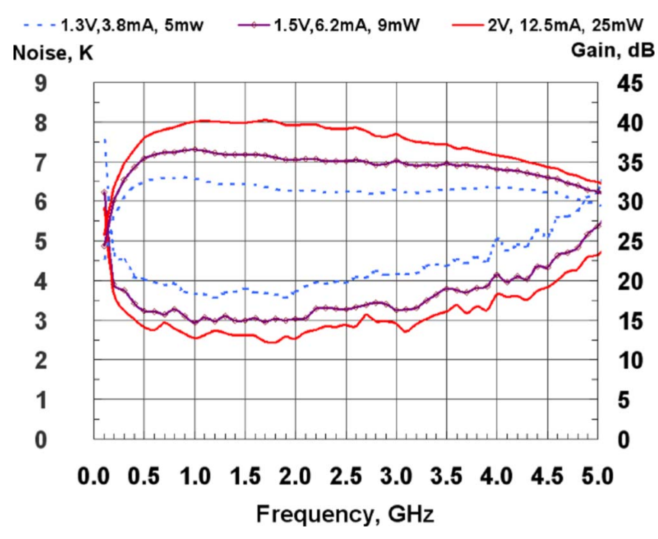


FIG. 10. (Color online) Gain (top) and noise of ST LNA at 17 K at three different bias values. Bias and temperature have little effect on the shape of the curves vs frequency and the values at midfrequency are given in Table II.

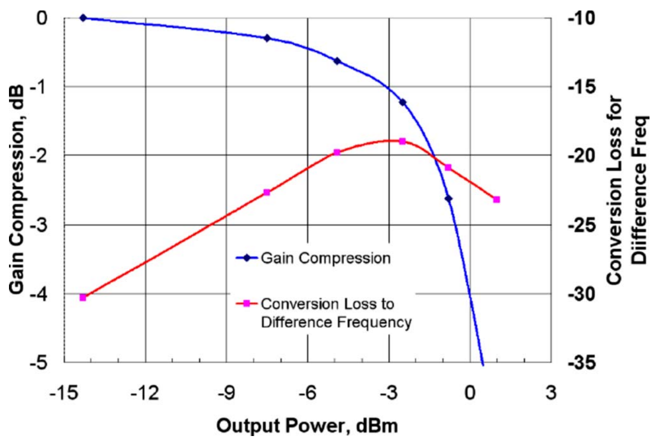


FIG. 11. (Color online) Gain compression and second order conversion properties of the ST LNA at 2 V,15 mA are plotted as a function of amplifier output power. A large signal at 2.1 GHz and a small signal at 3.43 GHz were simultaneously applied to the amplifier input. The output power (plotted as gain compression) and the power at the 1.33 GHz difference frequency (plotted as conversion loss) were measured as the 2.1 GHz power was varied.

state-of-the-art radio astronomy systems. Of particular significance is the combination of very low noise at cryogenic temperatures, input and output power matches, a decade of bandwidth, and low power consumption.

## ACKNOWLEDGMENTS

We acknowledge the contribution through Pascal Chevalier, STMicroelectronics, of the excellent experimental transistor used in the ST amplifier.

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